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Characterization of Reinforced Concrete Bridges Using Dynamic Response Measurements for Use in Load Capacity Estimation

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Final report

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ABSTRACT: The U.S. Army Engineer Research and Development Center (ERDC) is leading research efforts for the development of rapid bridge load-capacity assessment tools for the military, otherwise known as Military Load Classification (MLC). These tools may be used in the evaluation of the effects of heavy military vehicles on civilian bridges and are based, in part, on field tests of concrete bridges. This field testing procedure is aimed at determining the MLC of a bridge by first estimating girder stiffness and considering load distribution effects associated with a test vehicle. This approach, while capable of providing the desired MLC estimate, does not provide an adequate measure of uncertainty or confidence in the estimate, since the field measurement may mask actual damage states in the bridge.

Assessing the current condition of a bridge is a key component in the determination of its load-carrying capacity. As a result, tests in which the true condition of the bridge is determined can be useful in assessing the relative uncertainty or even the appropriate confidence level of the MLC estimate. This study describes field testing procedures using ambient, impact, and wave speed techniques on reinforced concrete bridges owned by the Virginia Department of Transportation. The ambient response measurements were used to determine fundamental characteristics including resonant frequencies and mode shapes, while the transient tests were designed to provide some measure of the relative condition that may exist between girders in the bridge. These measurements will supplement other measurements acquired using test vehicles and surveying techniques.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurements used in this report can be converted to SI unit as follows:

Multiply	By	To Obtain
cubic feet	0.028317	cubic meters
feet	0.304800	meters
g, standard free fall	9.806650	meters per second squared
inches	25.4	millimeters
miles	1.609347	kilometers
pounds (force)	4.448222	newtons

Preface

This report describes a research study developed by Harvey Mudd College in collaboration with the U.S. Army Engineer Research and Development Center (ERDC) consisting of the development of field-testing procedures that use ambient, impact, and wave speed techniques for assessing fundamental response characteristics and condition evaluation of reinforced concrete T-beam bridges. Results from these tests will assist in the evaluation of suitable methodologies for rapid load-capacity assessment of reinforced concrete bridges under military vehicle loading currently under development at the ERDC. The study was part of the AT40 Direct-Allotted 159T Tele-Engineering Development RDT&E Work Package, Work Unit TE004, "Rapid Load Capacity Assessment of Reinforced Concrete Bridges," which is sponsored by Headquarters, U.S. Army Corps of Engineers.

This publication was prepared by personnel from Harvey Mudd College and the ERDC, Geotechnical and Structures Laboratory (GSL), Vicksburg, MS. The research described herein was conducted by Professor Ziyad H. Duron, Messrs. Daniel Sutoyo, and Gene Lee, Harvey Mudd College, and by Ms. Yazmin Seda-Sanabria, Structural Engineering Branch (StEB), GSL. Ms. Seda-Sanabria prepared this publication under the general supervision of Dr. David W. Pittman, Acting Director, GSL; Dr. Robert L. Hall, Chief, Geosciences and Structures Division, GSL; and Mr. James S. Shore, Chief, StEB, GSL.

COL James R. Rowan, EN, was Commander and Executive Director of ERDC, and Dr. James R. Houston was Director.

1 Introduction

The U.S. Army Engineer Research and Development Center (ERDC) is leading efforts toward the development of rapid bridge load-capacity assessment tools for the military. These tools may be used in the evaluation of the effects of heavy military vehicles on civilian bridges and are based, in part, on field tests of concrete bridges. These tests are designed to assist the evaluation of suitable methodologies for rapid load-capacity assessment of reinforced concrete bridges under military vehicle loading.

A field test program was conducted in which static and dynamic testing of two reinforced concrete bridges were performed. Testing was performed under the direction of research engineers at ERDC in collaboration with researchers from Virginia Polytechnic Institute and State University (Virginia Tech) and Harvey Mudd College. Test vehicles were used to traverse the bridges, and induced response was captured using deflectometers and a laser measurement system under the guidance of ERDC and Virginia Tech researchers. In addition to these measurements, researchers from Harvey Mudd College conducted separate testing on one of the bridges. This testing included ambient, impact, and wave speed procedures designed to extract bridge response characteristics and assess bridge condition. The collection of information gathered during the test program will provide insight to help determine amounts of steel reinforcement in main girders. Obtaining field estimates of steel reinforcement is a critical step in assigning load carrying capacities to a bridge.

The purpose of this report is to describe the field testing completed using the ambient, impact, and wave speed techniques on a reinforced concrete bridge. Assessment of the ability of the various techniques to extract fundamental response characteristics is presented, and proposed diagnostic procedures are also discussed.

2 Description of RTE 697 Bridge

The RTE 697 Bridge is located on Route 697 over Mill Creek near Rocky Mount, VA. The bridge, constructed in 1979, is 120 ft[1] long and has a roadway width of 26 ft. A schematic of the bridge, which shows an elevation, plan, and transverse section, is shown in Figures 1, 2, and 3. Two interior bridge piers provide support for the deck located 40 ft inward from each abutment. Section details of the abutment, pier, and bearing supports are shown in Figure 4. The deck surface is grooved and is supported by four reinforced concrete T-beams (hereafter referred to as girders). During the testing program, unlimited access was available to all areas of the upper deck and the underside of each section.

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page v.

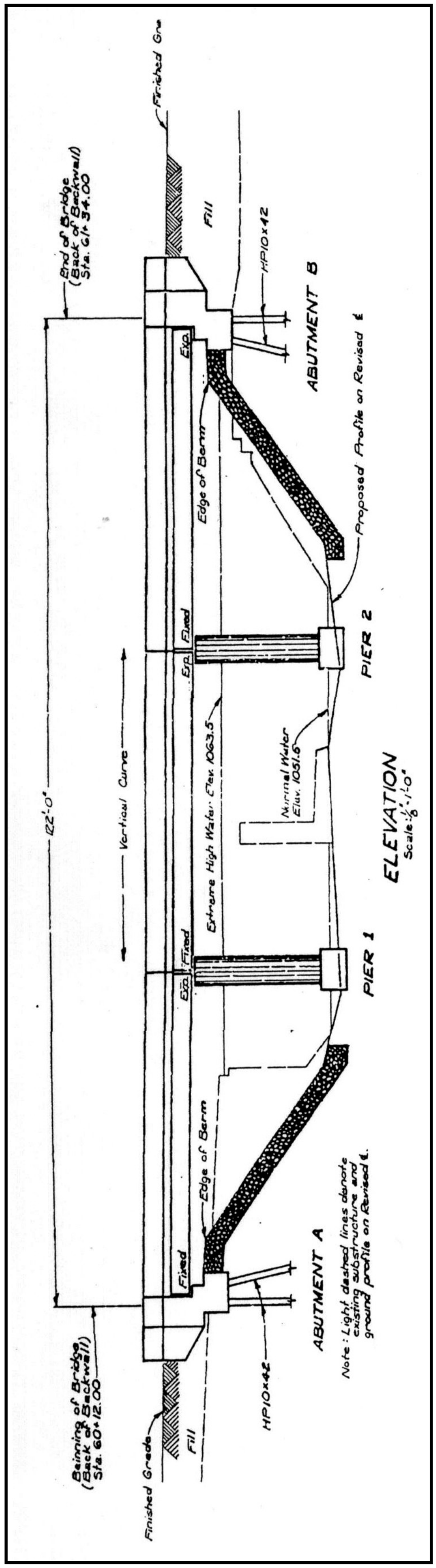


Figure 1. Elevation section of the RTE 697 Bridge near Rocky Mount, VA

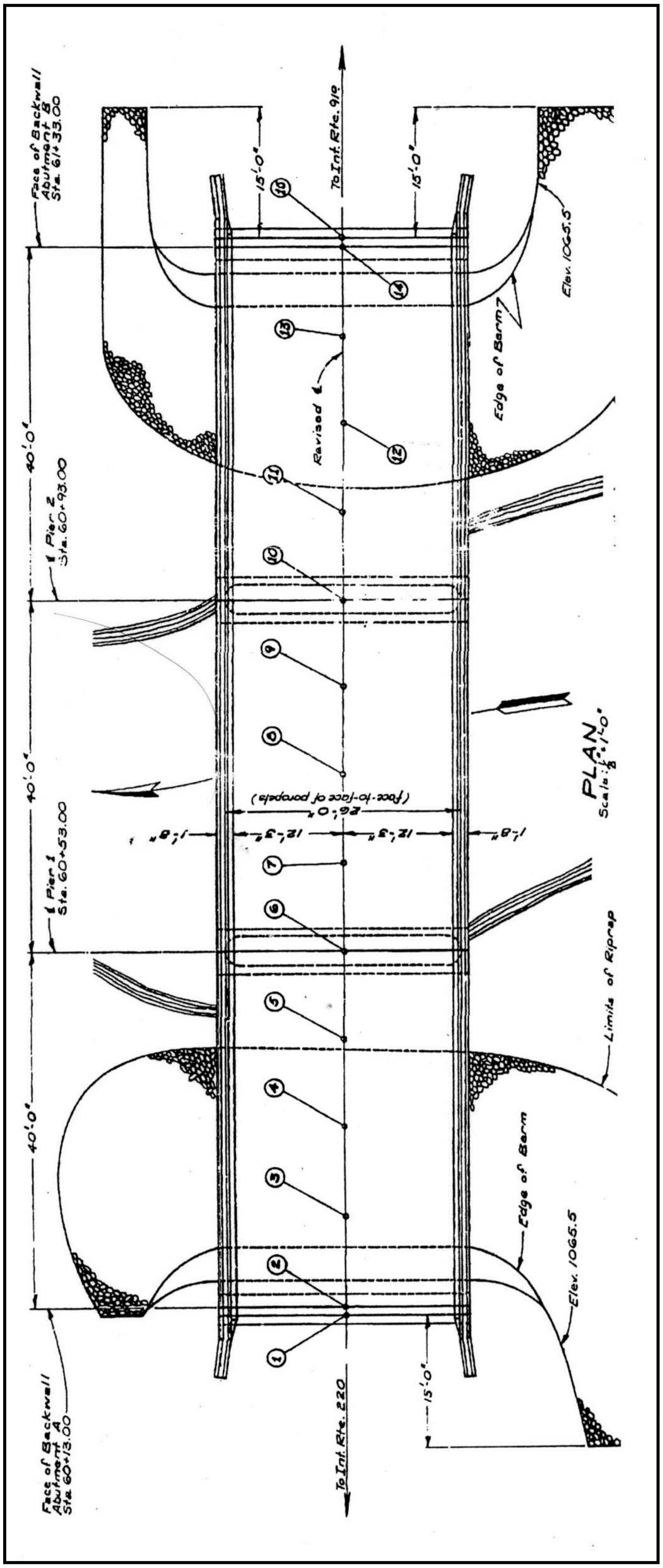


Figure 2. Plan view of the RTE 697 Bridge

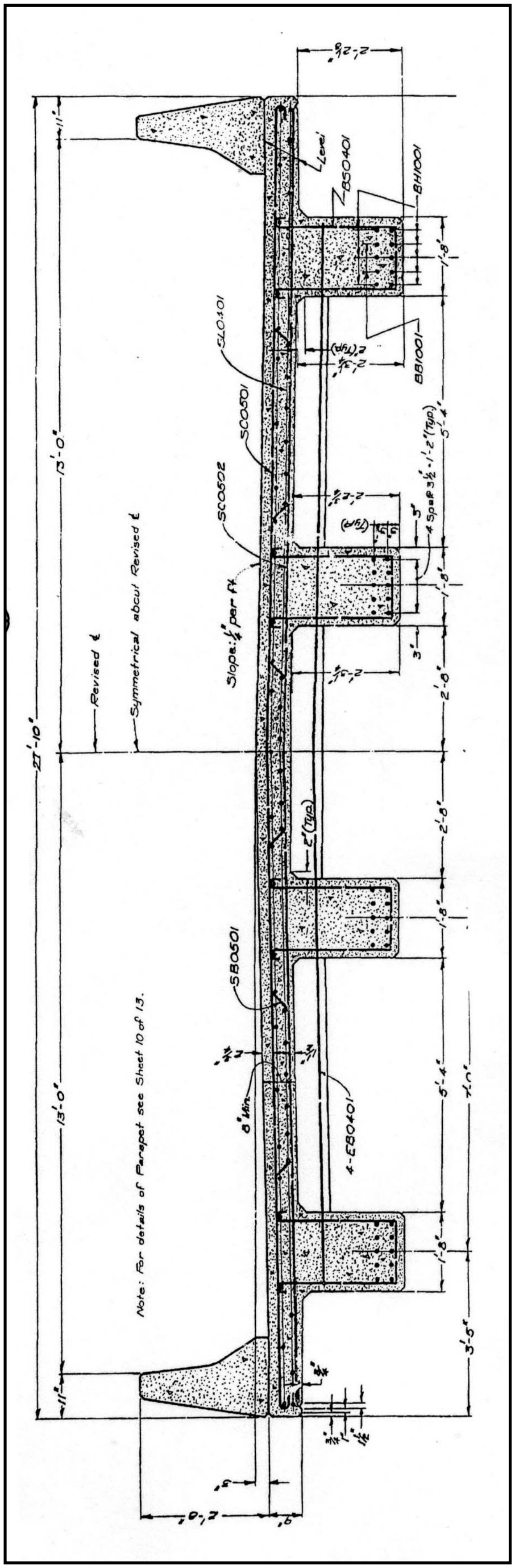


Figure 3. Transverse section of the RTE 697 Bridge

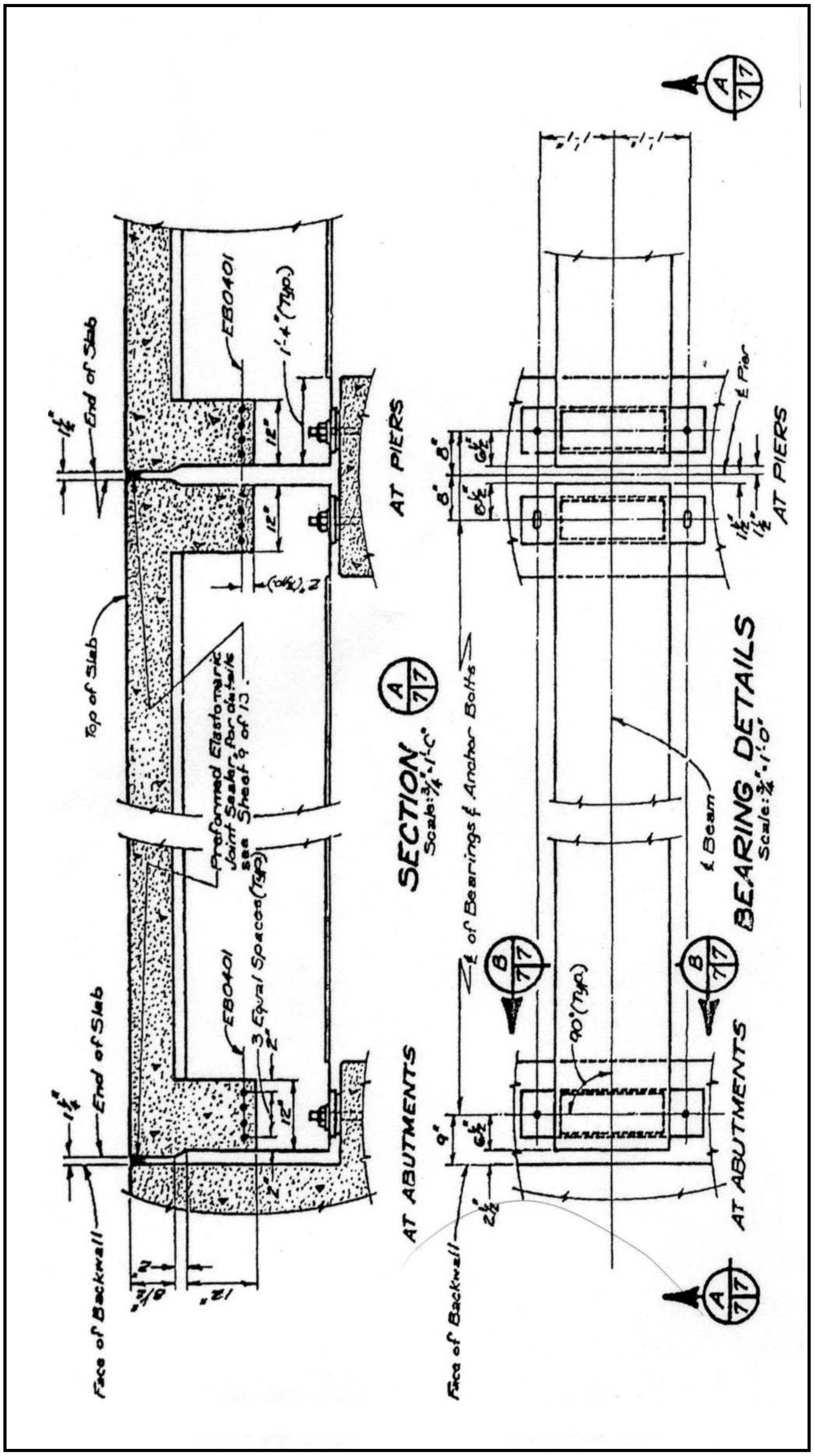


Figure 4. Section details at abutment and interior pier supports

3 Description of Test Objectives – Statement of Work (SOW)

Original test objectives included the evaluation of ambient, impact, and wave speed testing techniques applied to a reinforced concrete bridge for dynamic characterization. The information from these evaluations, coupled with the measurements acquired during testing with the Test Vehicles, could lead to enhanced confidence in estimates of steel reinforcement. An SOW is provided below.

Statement of Work (SOW)

These tests will be used to obtain baseline information that characterizes the dynamic behavior of a reinforced concrete bridge. Specifically, ambient, impact, and wave speed testing techniques will be used to evaluate bridge response behavior.

The effectiveness of field-testing techniques suitable for diagnostic procedures that could be used to evaluate bridge condition will be assessed.

Description of Approach

The SOW and subsequent effort on the RTE 687 Bridge were intended to supplement the main research effort and provide a context for evaluating results obtained during testing in which a Test Vehicle was used to excite the bridge.

The approach taken involved the application of well-known testing techniques in which random, transient, and propagating waves are captured on the bridge. Random responses are induced by ambient conditions at the bridge that include wind, water, and vehicular traffic excitation sources. Transient responses are induced by using a calibrated hammer to impact the bridge deck. Propagating waves are captured at the ends of each support girder and are induced by a single impact on the bridge deck. The transient responses are used to identify time of wave arrival at each end and provide estimates of wave speeds in the bridge. All responses are captured using highly sensitive accelerometers capable of detecting low-level magnitude and low-frequency behavior without altering magnitude and phase response behavior.

Description of Completed Test Schedule

A description of the tests completed is provided in Table 1 below.

Table 1
Description of Completed Tests on RTE 697 Bridge

Test Period	Impact Testing	Ambient Testing	Wave Speed Tests
18 October 2002	Single impact location on east span. Deck responses acquired in each span for single impact location.	Reference locations located in center and west span. Deck responses acquired in each span with reference locations fixed.	Along entire bridge length over each girder and across intermediate supports. Responses acquired at girder ends only.

4 Description of Instrumentation and Test Procedures

Instrumentation and test procedures were selected and designed to provide efficient data acquisition and recording of time records during field tests. All responses on the bridge deck were acquired using Model QA-700 accelerometers manufactured by Honeywell. The accelerometer is housed in a small cylindrical case. It is insensitive to temperature fluctuations and is hermetically sealed. A servo-force-balance design, the accelerometer produces an output current proportional to the surface acceleration allowing the use of extended cable lengths (approaching 1,000 ft if necessary) without significant signal loss. At the signal conditioner (described below), the current output is converted into a voltage across a resistor providing a known voltage/acceleration (V/g) sensitivity. For the testing completed at the RTE 697 Bridge, a 10-V/g sensitivity was selected. The sensitivity coupled with the extremely low threshold of 1 μg makes the QA-700 particularly well suited for low-level testing of large civil structures.

Signal conditioning used for all testing included band-pass filtering and amplification. Filtering as set at 30 MHz (a first-order RC network) for the high-pass and at 25 Hz (a second-order Butterworth filter) for the low-pass frequency cutoffs. Amplification was accomplished using a two-stage amplifier set at Stage I (pre-low-pass filter) gains of 10 and Stage II (post-low-pass filter) gains of 6, for a combined amplification gain of 60. Gains were selected on the basis of ensuring against clipped responses in the presence of vehicular traffic over the bridge. Testing was completed under traffic-controlled conditions with the help of Virginia Department of Transportation (VDOT) personnel who controlled bridge access at each end. Data were acquired digitally at sampling rates of 250 samples per second for ambient responses and at a higher rate of 1,000 samples per second for the impact and wave speed responses. Ambient responses were recorded over a 6-min period (minimum), while impact responses were triggered using the leading edge of the force pulse over a 9-sec period. Time histories were acquired and stored to disk using an IOTECH DaqBook200 laptop controlled acquisition system.

Ambient Test Procedure

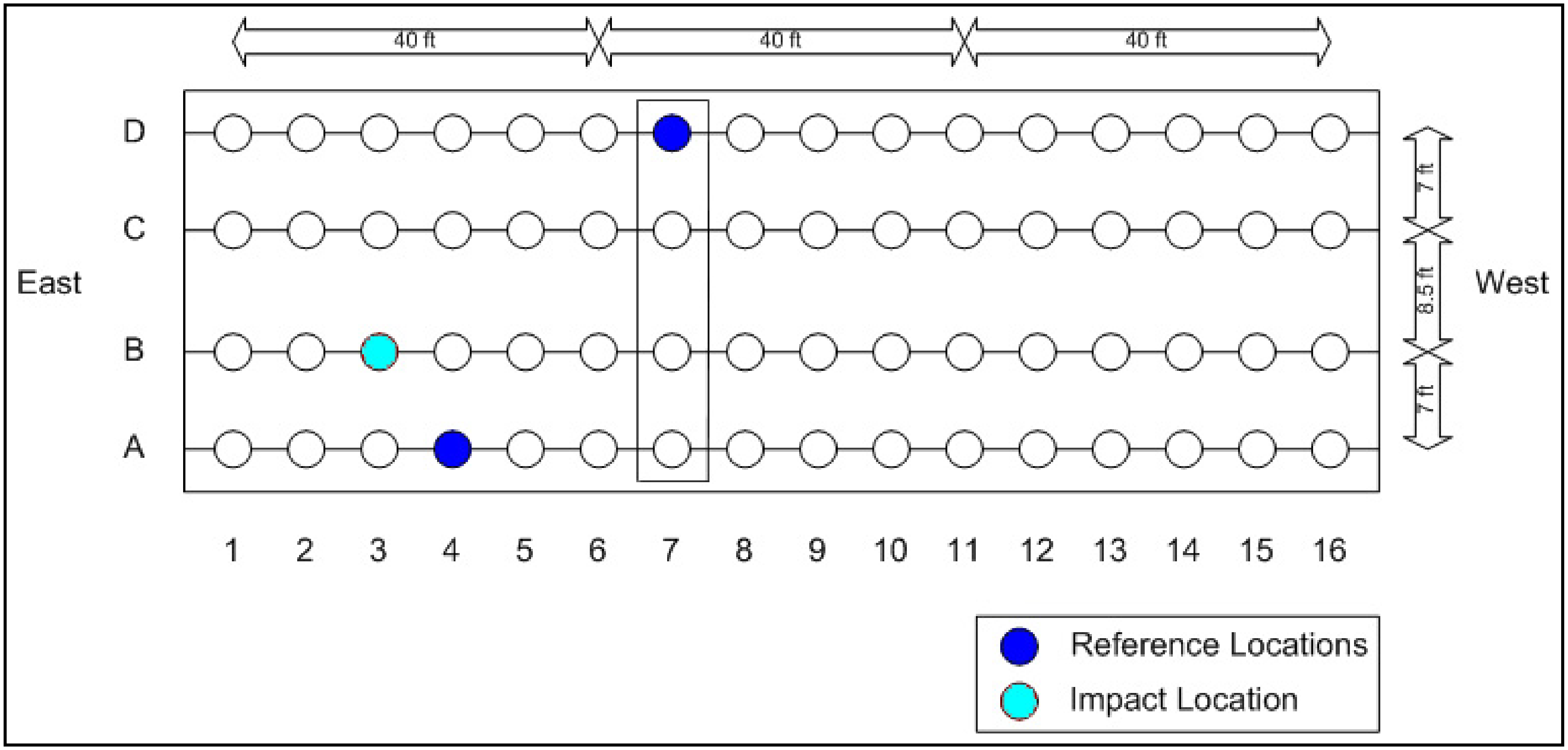
Ambient acceleration responses were acquired on the upper deck surface using the layout shown in Figure 5. Each hollow circle denotes a uni-axial measurement in which vertical accelerations were recorded. Each accelerometer was placed into a small mounting block and bolted onto a leveling platform. The platform was supported off the deck surface by three screws in tripod fashion, facilitating leveling procedures with a bubble level and secure placement on non-level areas of the deck. No bonding agents or adhesives were used to install the accelerometers on the bridge deck. The filled circles indicated at locations A04 and D07 mark reference locations that remained fixed during testing.

Five uni-axial accelerometer platforms were used to acquire response information at 64 locations on the deck. Each test consisted of placing three accelerometer platforms on the deck (for example, starting at locations A01, A03, and B01), leveling each platform to ensure vertical orientation. Two accelerometers remained fixed at the reference locations throughout the test. System checks were performed prior to acquisition and consisted of monitoring accelerometer output to verify operation, minimum signal drift, and the absence of clipped or saturated responses. At the end of each measurement sequence, the three accelerometers were moved or roved to the next set of locations. The process was repeated until all measurement locations on the deck were monitored. The ambient survey required 19 separate acquisitions and approximately 4 hr to complete.

Concerns regarding traffic effects during ambient testing typically involve unpredictable or excessively high amplitude signal level associated with vehicular traffic and tire impact over joints in the bridge deck. In most instances, ambient testing can be carried out even in the presence of vehicular traffic (both under and over the bridge). At the RTE 697 Bridge, traffic conditions were controlled by VDOT personnel resulting in reduced speeds over the bridge that contributed to manageable response variability. An assessment of the data quality observed during ambient testing is discussed in Chapter 7.

Impact Test Procedure

Impact testing employed the same measurement layout used during the ambient tests. Unlike the ambient tests, however, a measurable excitation signal was provided by a calibrated hammer load cell upon impact. This force pulse was used as a reference signal for the transient response analysis performed. Previous experience with impact testing on large civil structures indicates that coherence variability is typically minimal after the sixth consecutive impact. This suggests that satisfactory confidence can be achieved in spectral estimates of frequency response and power spectral density from a test procedure in which six repeated impact/response data sets are acquired. As a result, for each measurement location, responses were acquired from a series of six or more impacts. Data acquisition was triggered by the leading edge of the force pulse.



<u>Note:</u> Locations A07 – D07 (enclosed by the rectangle) correspond to the impact locations for the wave speed tests.

Figure 5. Measurement layout for placement of accelerometers for both ambient and impact tests

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Also, a small amount of pretrigger was included to ensure the capture of the transition region prior to impact for the force pulse and of the wave arrival at each measurement location.

To minimize the analysis effort of the impact responses and to provide as good a data set as possible, impacts on the bridge were performed and responses were acquired only during periods of no traffic in the vicinity of the bridge. Although not a necessary condition for the conduct of bridge impact testing, vehicular traffic-induced vibration levels can obscure the transition from ambient to transient behavior. Transient responses must be acquired over a sufficient period of time to ensure capture of wave arrival, transient response, and return to preevent (ambient) conditions for each impact.

5 Description of Sample Test Results

This chapter presents a sample of the test results in the form of time-histories and computed spectral quantities from both ambient and impact tests. Wave speed test results are discussed in Chapter 6. Spectral quantities derived from measured responses include power spectral density (PSD) and frequency response (FRF) and coherence functions.

Ambient Test Results

Ambient acceleration response at location A07 is shown in Figure 6 and is typical of the type and quality of ambient acceleration recorded during the test in which traffic-induced transient behavior is clearly observed. For a typical ambient test, the absence of traffic-induced transients is preferred so that instrument settings can be chosen to ensure adequate ambient data quality. In the presence of large transient spikes (as is seen in the responses in Figure 6), care must be taken to select amplification settings that avoid (signal) clipping or (instrumentation) saturation, while providing sufficiently high gains to elevate low-level ambient bridge response behavior. The portions of the responses that are actually the desired ambient components appear as straight lines between each transient. A close-up of the "random" portion of the response at A07 is shown in Figure 6.

During the ambient tests on the RTE 697 bridge, a free flow of traffic over one lane of the bridge was required at all times. Hence, traffic-induced transients could not be avoided during any portion of the ambient tests. The low-frequency trend observed in the response at A07 is presumed to be associated with changing conditions in the bridge, since a thorough instrumentation checkout was performed during the test and revealed no malfunctioning components. Since the trend was not uniformly observed throughout the measurement layout during the ambient tests and was restricted to a small number of locations, the trend was removed during postprocessing.

The PSD estimates taken from single locations in each of the three spans are shown in Figure 7. The general character of the PSDs is typical of measured responses in which signal-to-noise ratios are less than optimal contributing to the broad-band, broad-peak behavior as shown. These responses are consistent with

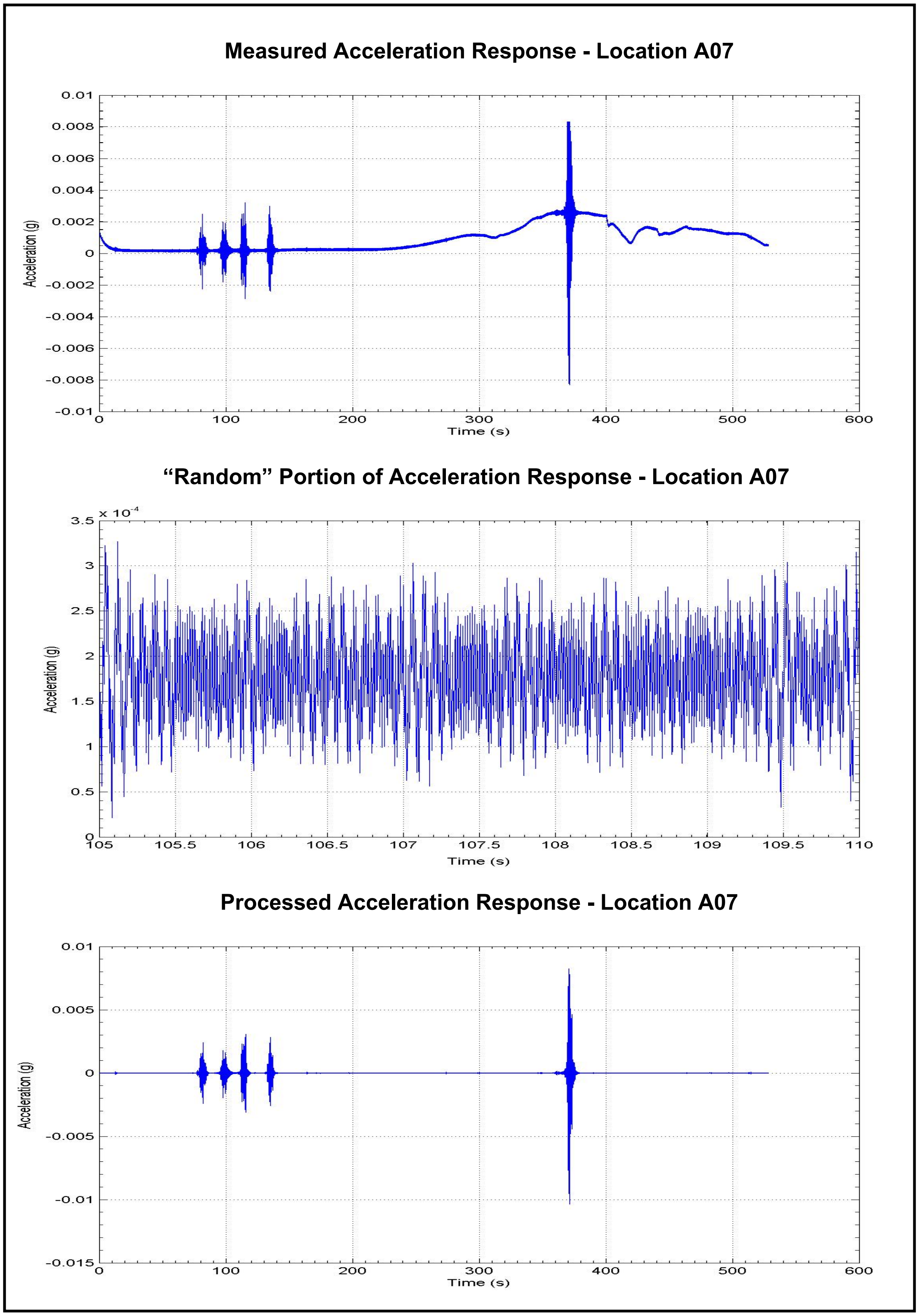


Figure 6. Typical time data acquired from October 2002 ambient test

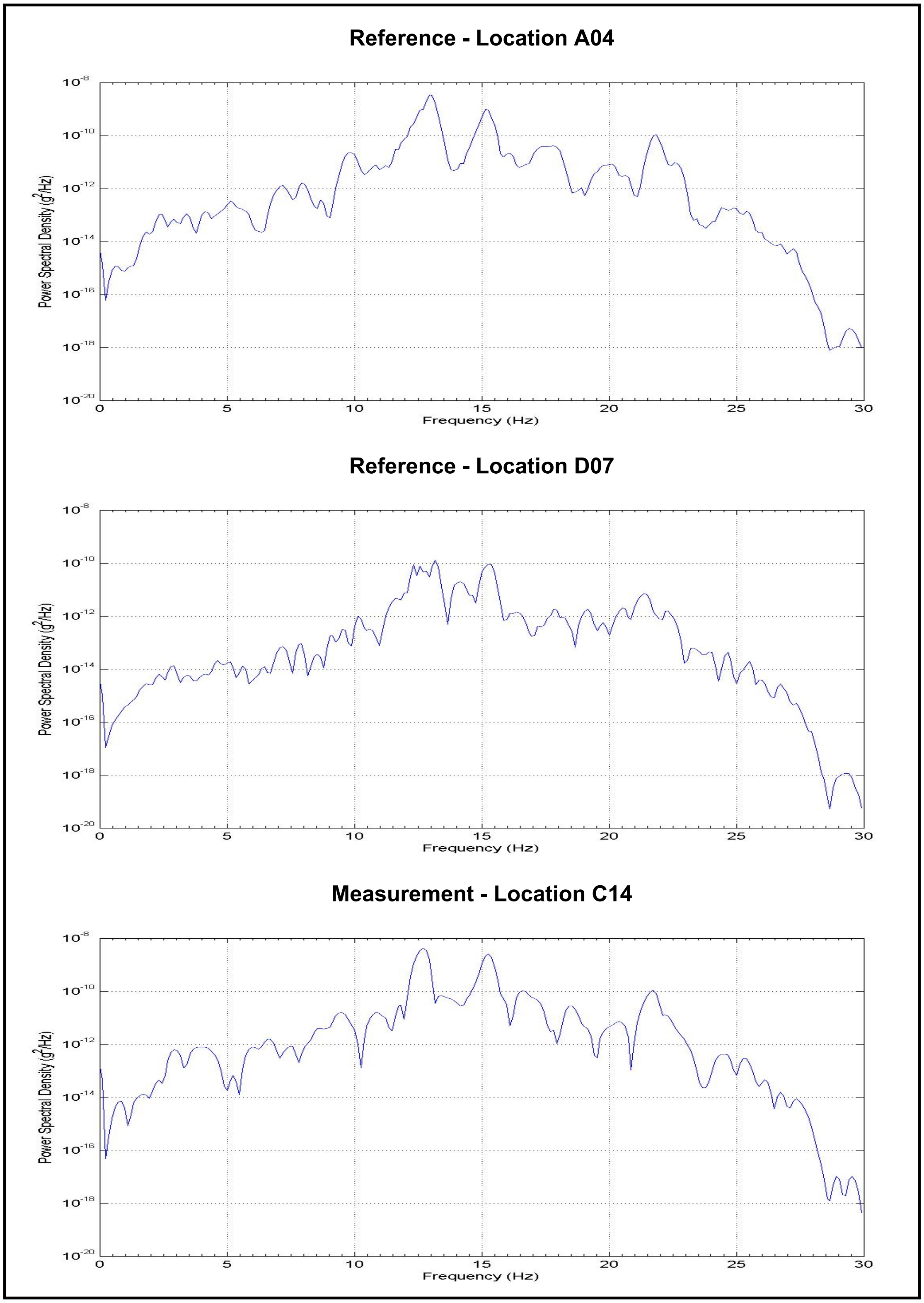


Figure 7. Typical power spectral density (PSD) estimates obtained from ambient tests

the inability to select sufficiently high gains during testing because of the large transient spikes and the desire to avoid clipping or saturation. Although not performed, alternate spectral analyses based on the Maximum Entropy Method could provide spectral estimates with enhanced confidence. Notwithstanding, estimates of frequency response and coherence functions shown in Figure 8 were judged to be satisfactory for this test.

Coherence levels are shown to be approaching unity (and, greater than 0.6) in the vicinity of resonant FRF peaks that can be considered as candidate resonances for the bridge. Coherence is used as a measure of statistical reliability and a measure of the repeatability of response behavior derived from one section of measured response to another. Ideally, sustained levels of coherence (near unity) around resonant peaks (in either PSD or FRF) provide confidence in identifying peaks as bridge resonances. However, as shown in Figure 8, coherence levels approach unity only in narrow bands around select peaks, providing further indication that the signal-to-noise ratios in the measured responses were less than adequate. Phase response at location C14 taken with respect to the response at the reference location A04 is shown in Figure 9.

Impact Test Results

Time-histories of acceleration responses and force pulses acquired during the impact tests are shown in Figures 10 and 11. Impact testing was performed using a commercially available calibrated impact sledgehammer to induce measurable transient responses in the bridge. The hammer was used to impact the bridge at location B03, and transient acceleration responses were acquired at locations on the bridge deck that coincided with the locations monitored during the ambient tests. Responses in the vertical direction at each location were acquired from multiple impacts (a series of six or more for each measurement). The VDOT provided adequate traffic control that allowed testing to be performed in the absence of traffic.

The response shown in Figure 10 (top) is typical of transient responses acquired during the impact tests. The induced transient behavior, although easily identified by the short duration spikes in the response, is largely masked by the presence of a steady and large-amplitude signal. A close-up of the steady portion of the response (see Figure 10, center) reveals the presence of a sustained 60-Hz signal that resulted from a gas generator that was used to supply electrical power to the instrumentation during testing. The 60-Hz signal presented a problem in assessing signal quality onsite; however, since no line power was available near the bridge, researchers had no option other than to proceed with impact testing knowing that the 60-Hz signal was of the same magnitude as the induced transient behavior in the bridge. The bottom response shown in Figure 10 is the same measured response after postprocessing in which the 60-Hz component was removed. The resulting (processed) transients are typical of expected behavior, and evidence of good signal quality is seen in the relative symmetry about 0 *g* in each response.

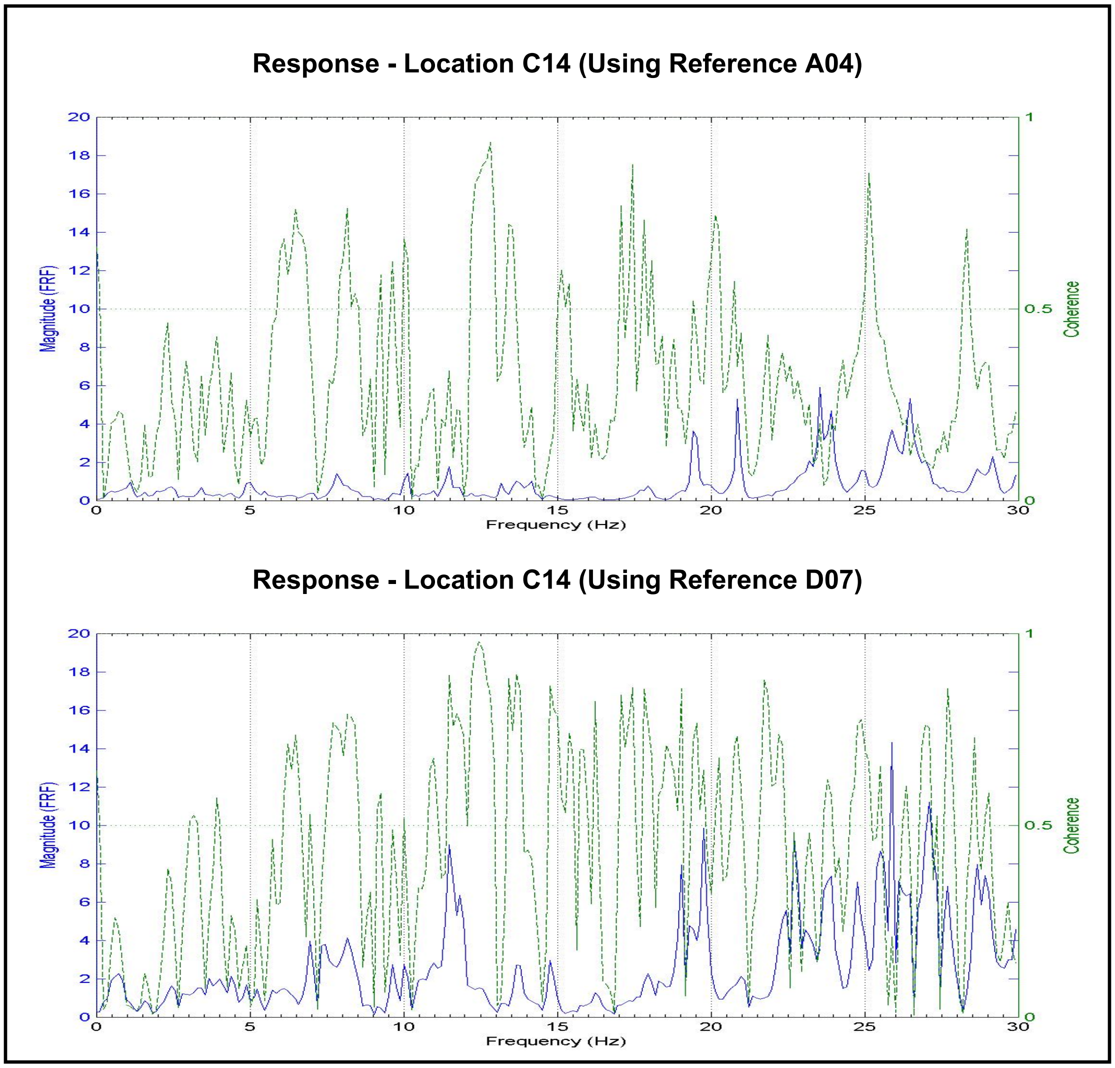


Figure 8. Frequency response and coherence estimates at location C14

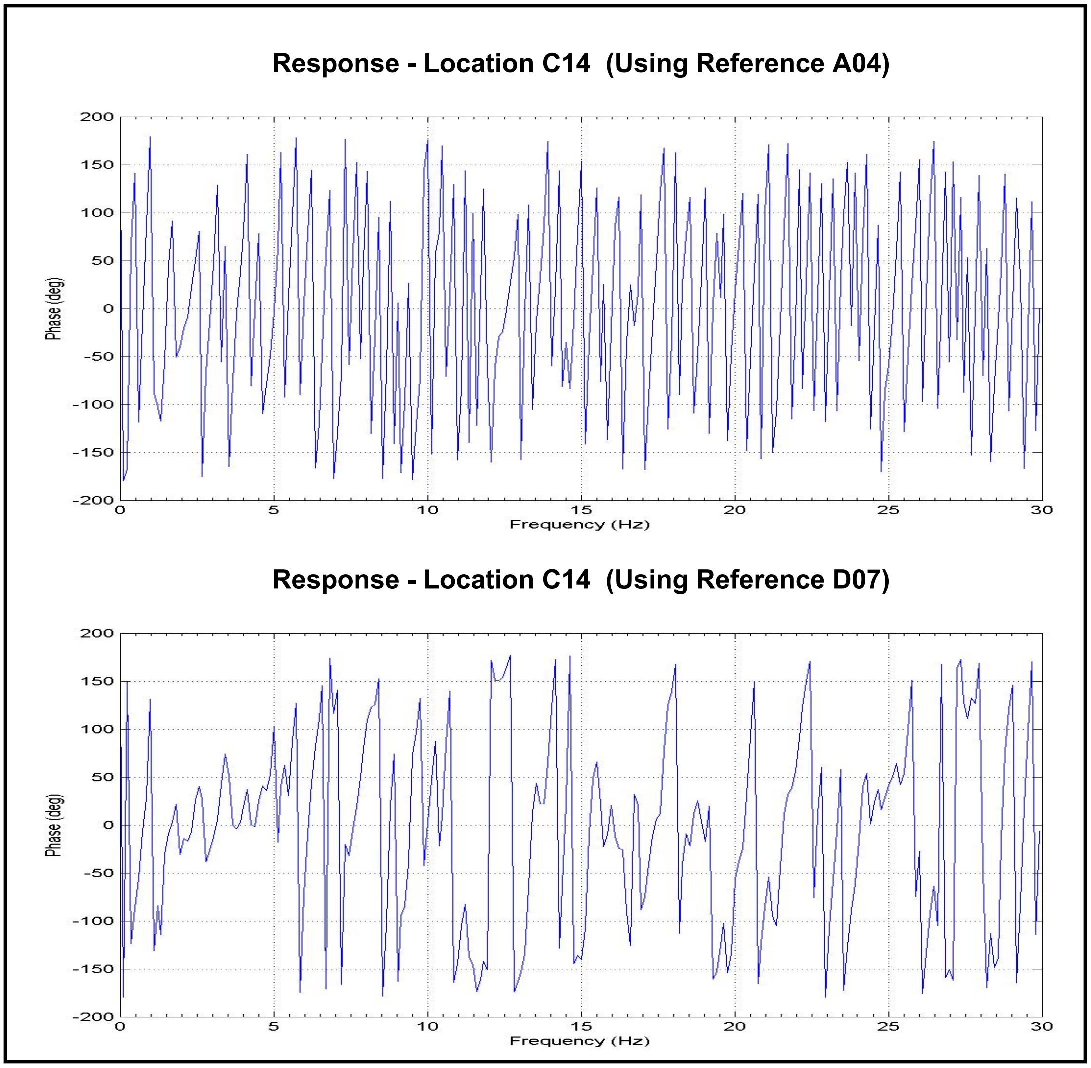


Figure 9. Phase response behavior at location C14

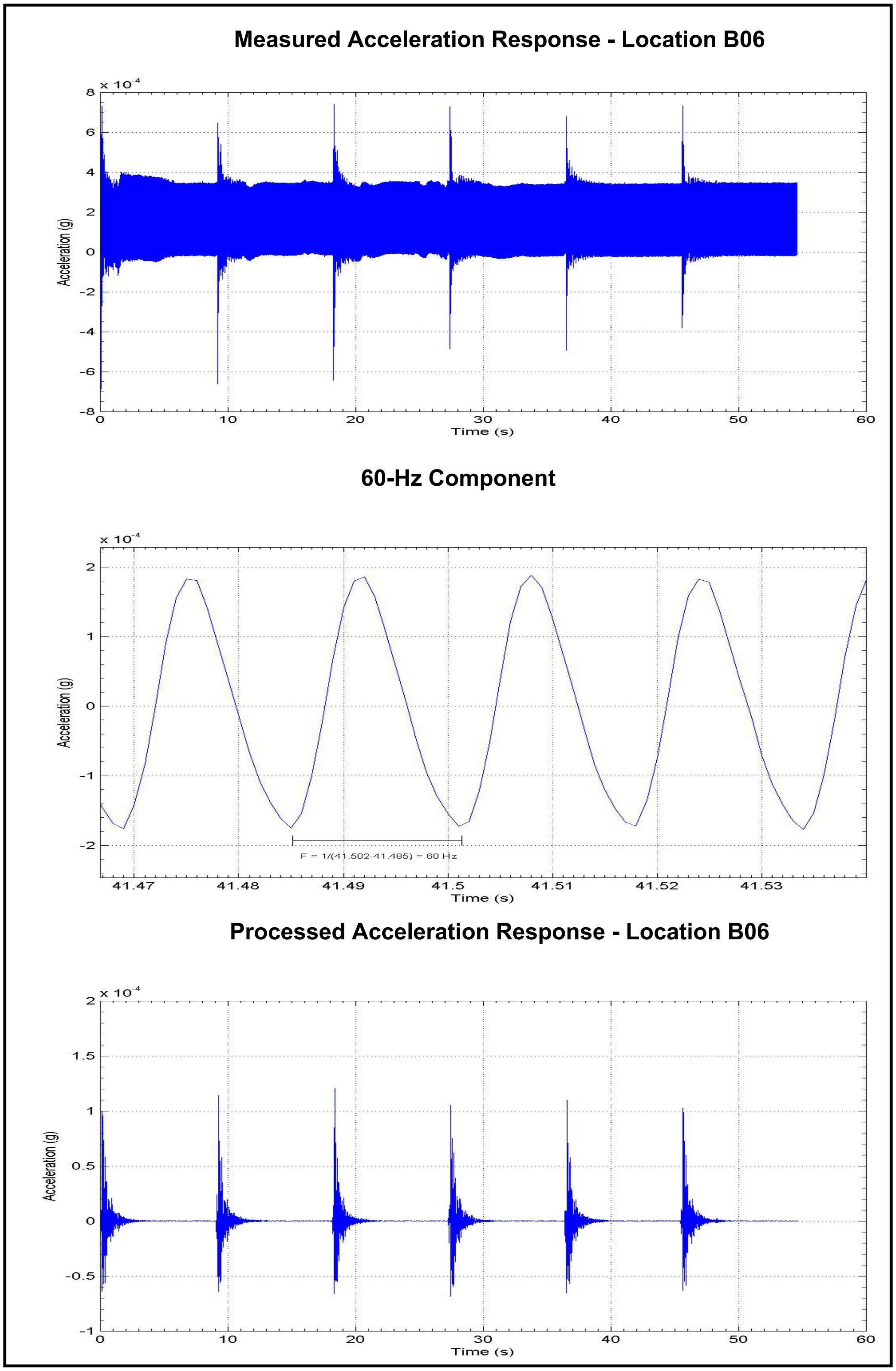


Figure 10. Typical acceleration response after removal of 60-Hz component

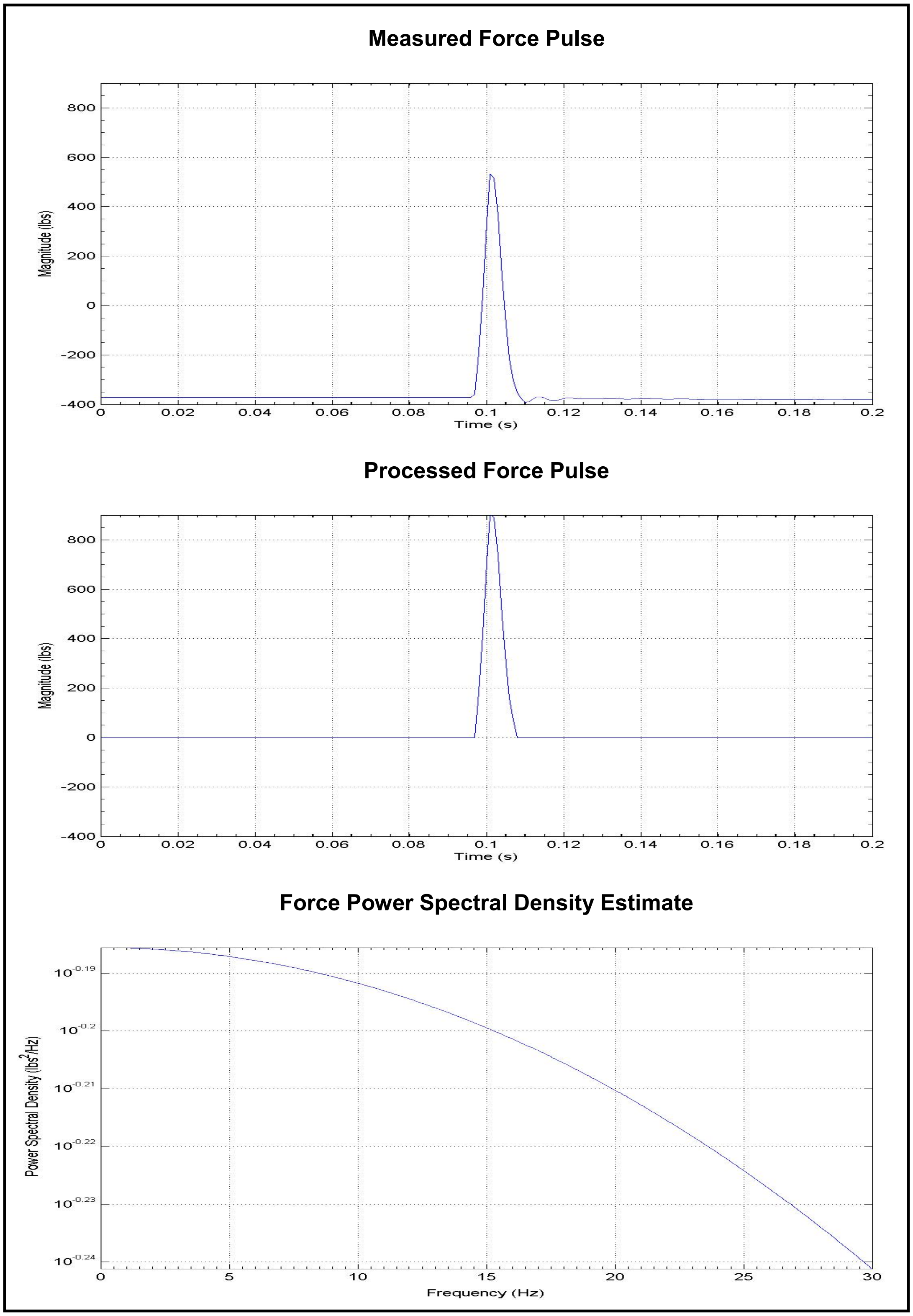


Figure 11. Typical force pulse characteristics acquired during impact testing

A sample force pulse obtained during testing is shown in Figure 11 (top) and is typical of the type and quality obtained during the tests. The pulse width (duration) is approximately 15 msec and is controlled (in part) by selecting the hammer tip (hardness) to provide sufficient energy to excite system resonances. The offset indicated in the measurement is associated with instrumentation and does not indicate the presence of a nonzero loading prior to the impact. The middle response shown in Figure 11 is the same force pulse after offset removal and the application of a rectangular window to remove unwanted ripple in the measurement prior to and after the force pulse itself. The associated PSD is shown in the bottom trace of Figure 11 and is consistent with the desired distribution of energy during an impact on the bridge.

PSD estimates derived from measured transient acceleration responses taken in each span at locations A04, A09, and A13 are shown in Figure 12. The estimates appear to indicate possible bridge resonance above 10 Hz, although a detailed assessment requires the examination of FRF and coherence estimates as well.

FRF and coherence estimates in each span are shown in Figure 13. As mentioned earlier, it is desirable to observe broad regions of high coherence (near unity) in the vicinity of FRF resonant peaks. This is clearly observed in the estimates shown in Figure 13. The relative FRF magnitudes (decreasing from location A04 to A09 to A13 as a result of impact at B03) are consistent with loss of impact energy from one span to the next. While impact energy is often lost across bridge decks, in the case of RTE 697 Bridge, the deck consisted of three separate decks supported on common interior concrete piers. This contributed to the dramatic reduction in response magnitude for locations (far) removed from the impact location at B03. Phase response behavior is shown in Figure 14.

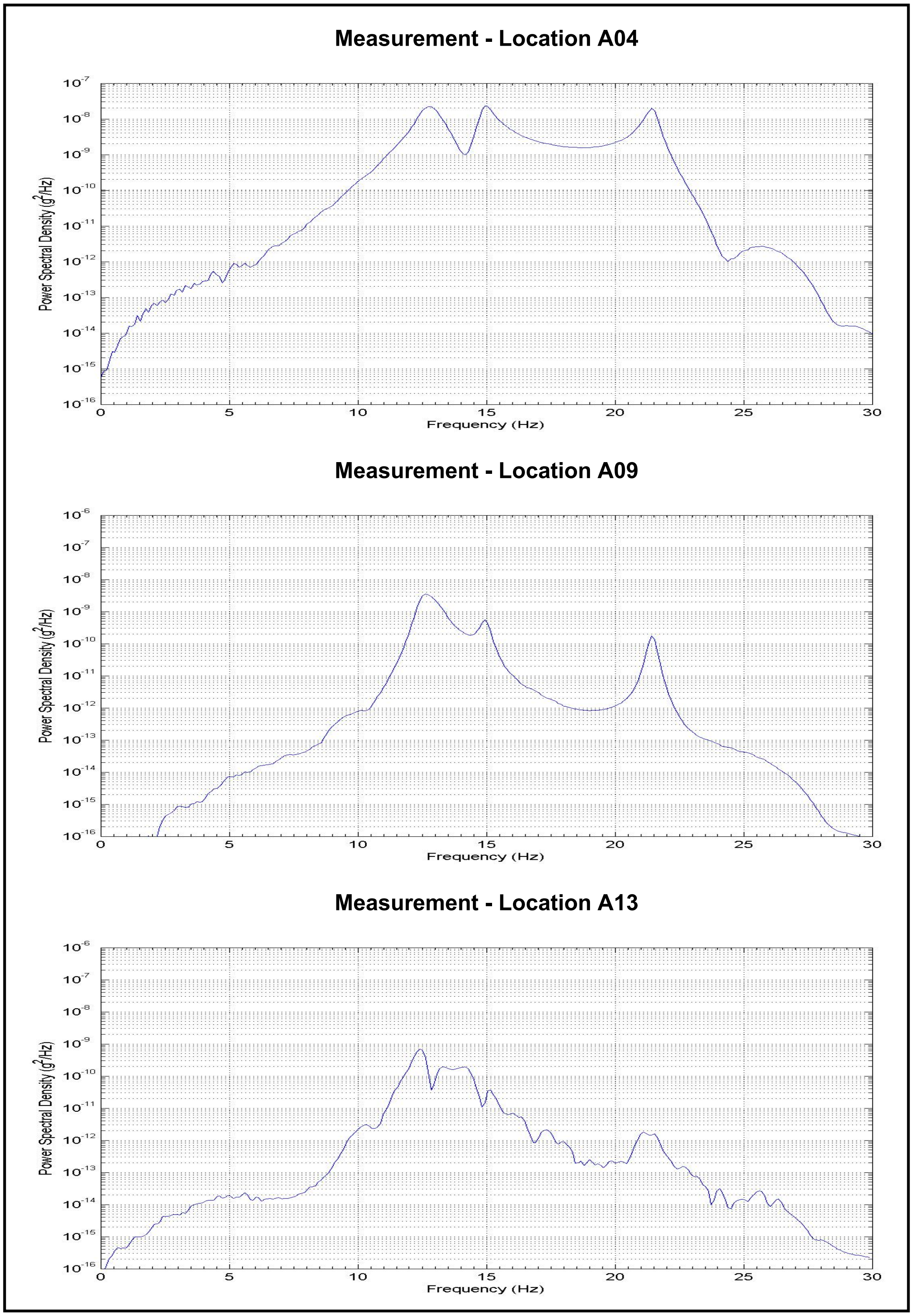


Figure 12. Typical power spectral density (PSD) estimates from impact tests

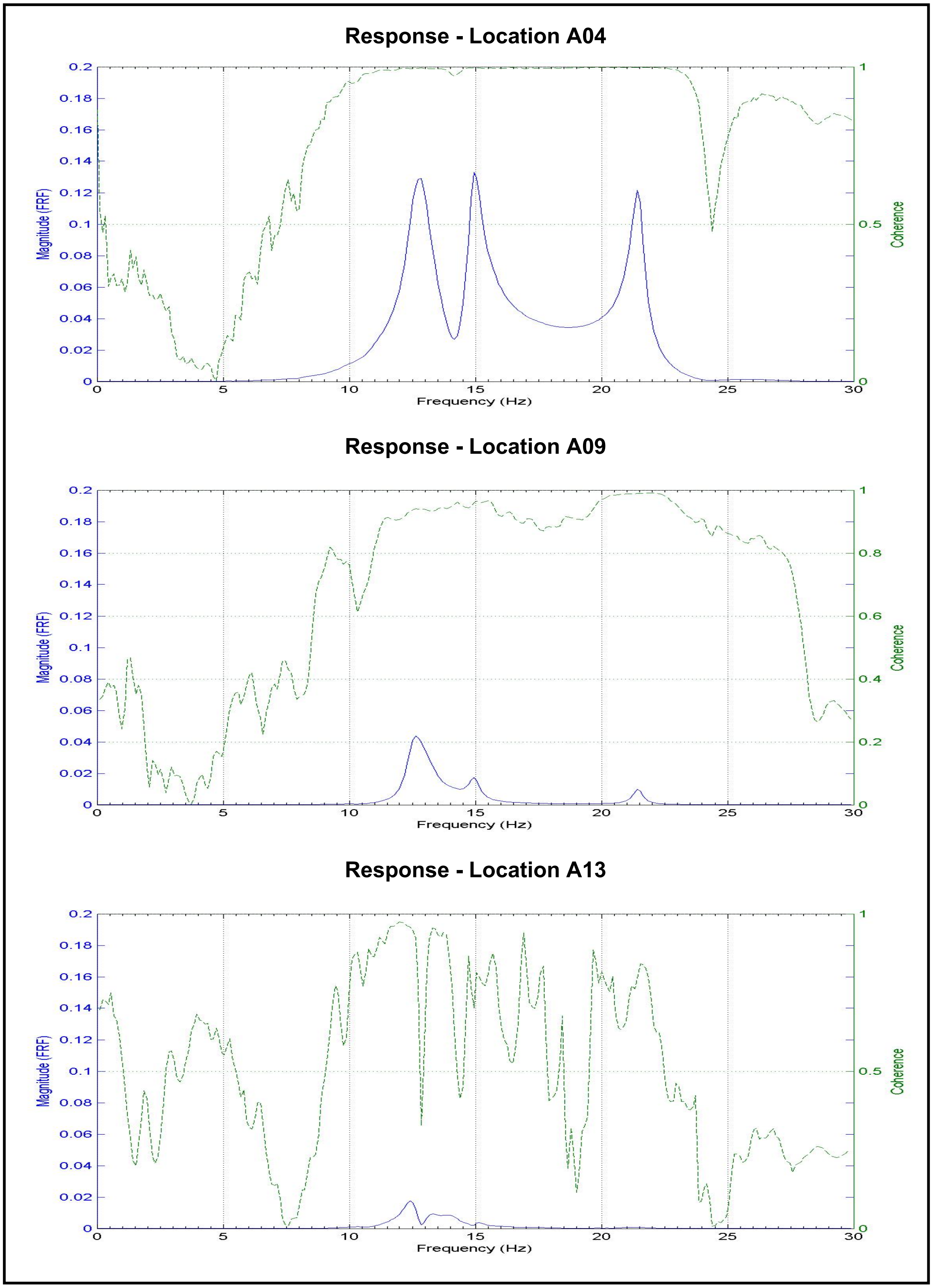


Figure 13. Frequency response and coherence estimates along girder A

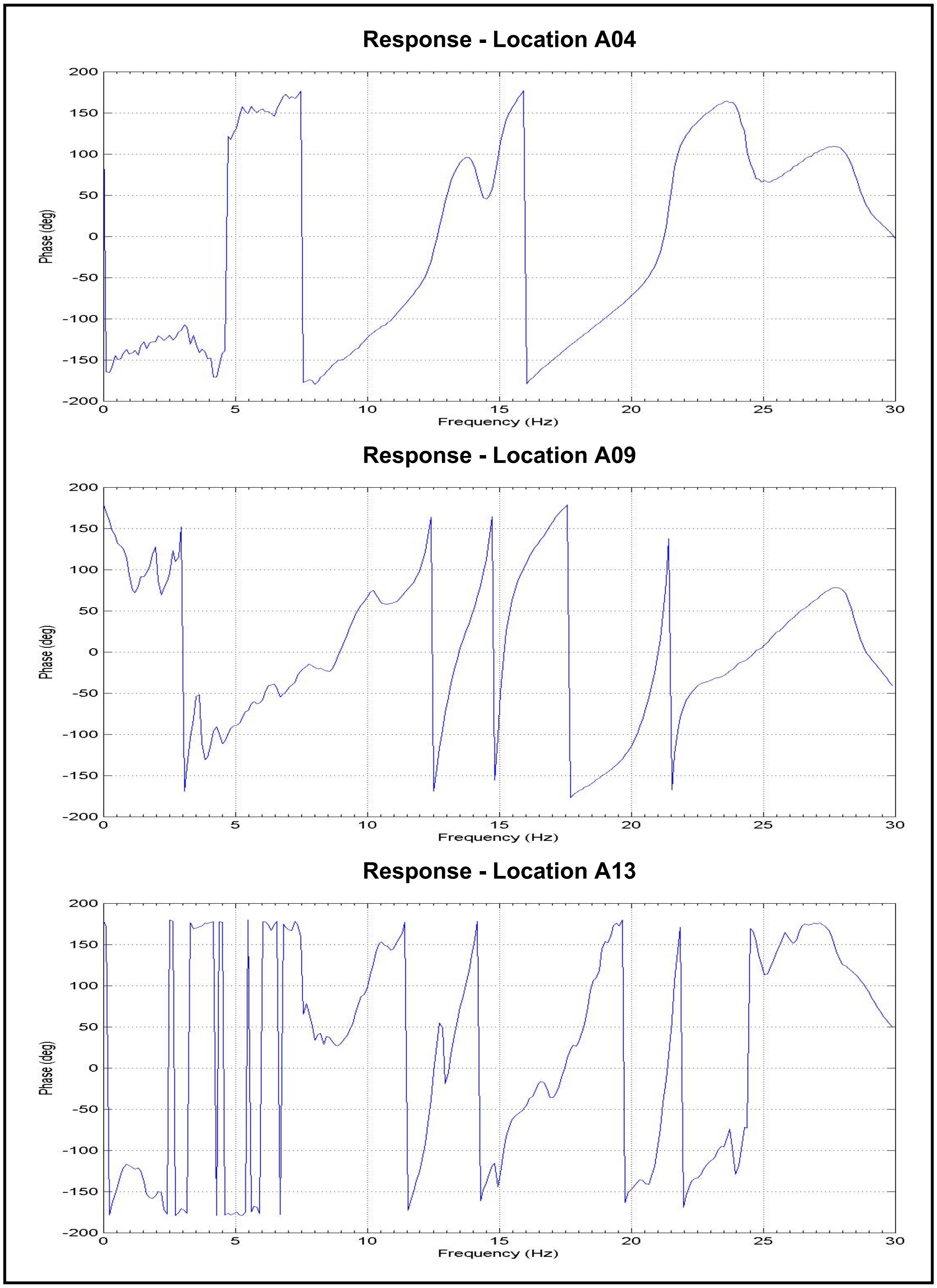


Figure 14. Phase response behavior along girder A

6 Description of Bridge Response Characteristics

Review of Response Behaviors

A review of both ambient and impact response behavior was completed to determine the fundamental, second, and third resonances in the bridge. Table 2 lists the resonant frequencies identified by examining spectral estimates and response shapes associated with candidate resonances.

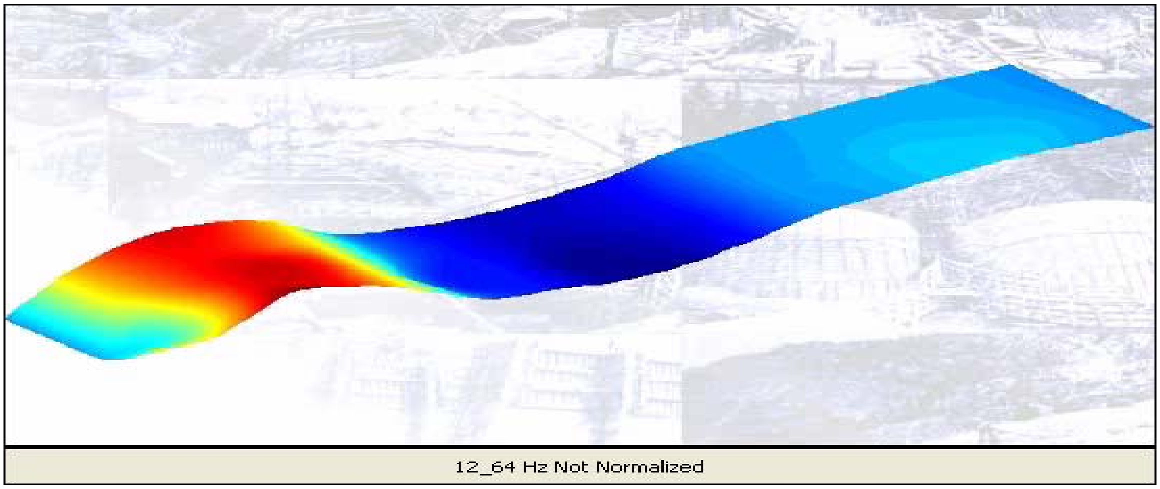
Table 2
Listing of Bridge Resonant Frequencies

Mode No.	Ambient, Hz	Impact, Hz
1	12.69	12.64
2	15.26	14.95
3	21.85	21.43

The agreement in resonant frequencies, shown in Table 2, between ambient and impact-derived estimates is considered to be good, especially considering the quality of the ambient data obtained. For example, the poor signal-to-noise ratio described earlier contributed to broad resonant peaks near 15 Hz obscuring an exact determination of resonant frequency.

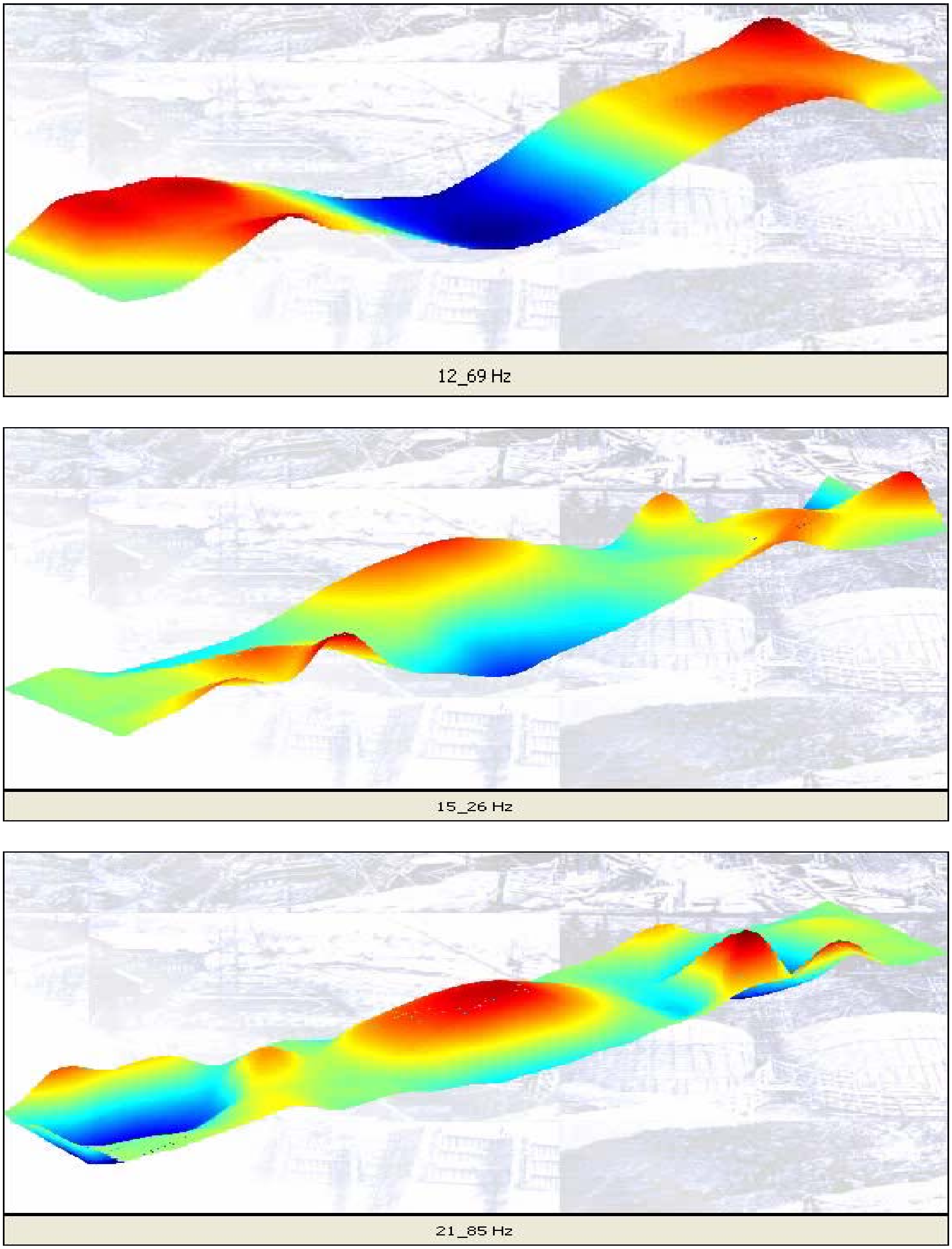
Response shapes derived from both ambient and impact response measurements are shown in Figures 15 through 17. A comparison of the measured response shapes provides further evidence of the good correlation between ambient and impact-derived bridge characteristics. The fundamental response shape is primary bending in each span with alternating phase, the second response shape is primary torsion, and the third response shape is a higher order bending (saddle) span response.

Damping values for the first three resonances were estimated from impact test results to be 4 percent (fundamental resonance), 2 percent (second resonance), and 1 percent (third resonance). These estimates were obtained using the half-power (bandwidth) method and a curve-fitting algorithm applied to measured FRF magnitude response.



<u>Note:</u> The relative magnitudes have been preserved across each span and the elevated response (left/most east span above) as a result of the impact location at B03 in the east span.

Figure 15. Measured fundamental response shape obtained from impact test results



<u>Note:</u> Frequency response was estimated using reference location D07. The response within each span has been normalized.

Figure 16. Measured (ambient) response shapes for the first three bridge resonances

Wave Speed Test Results

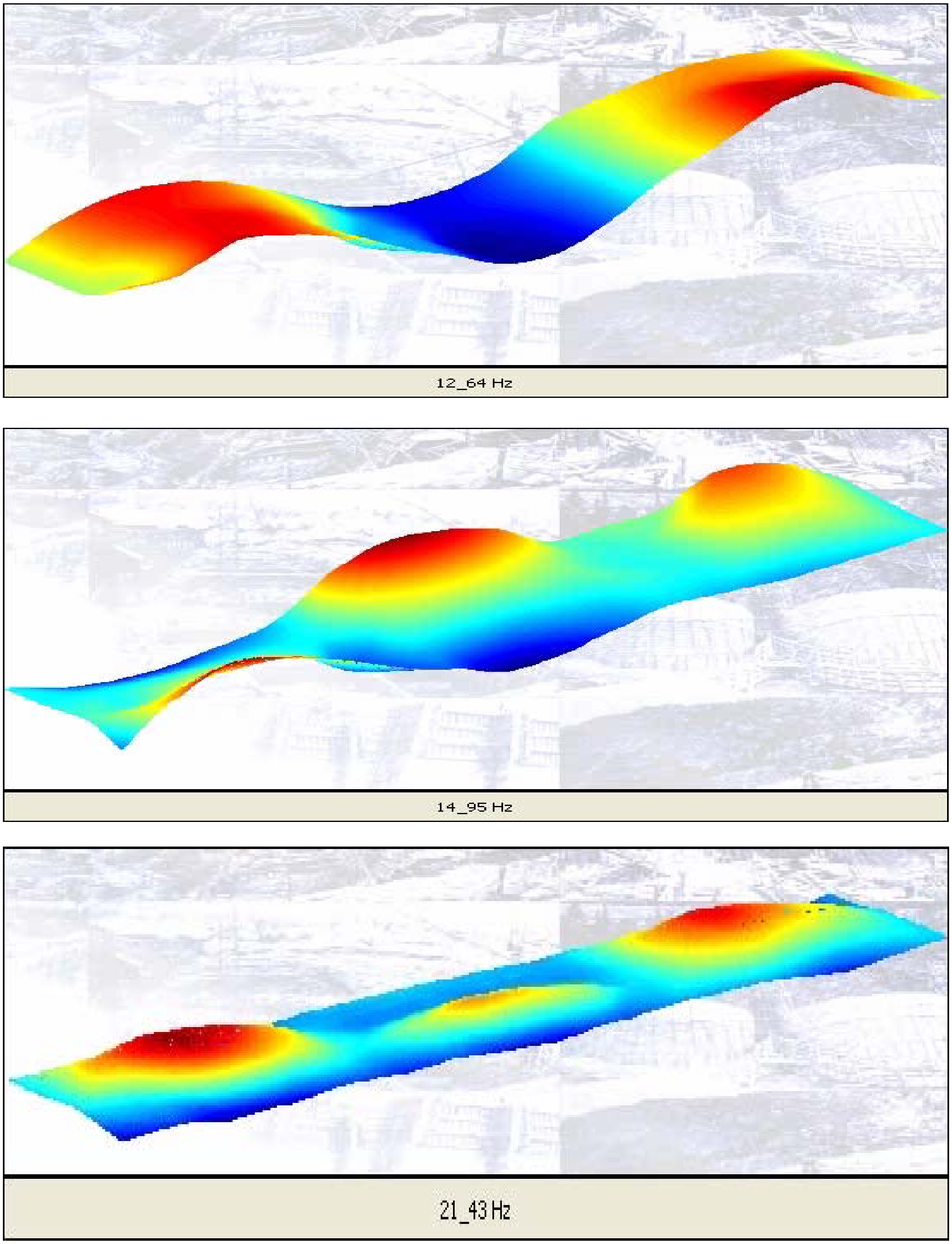
Wave speed testing was performed in which impacts at location 07 on each supporting girder and their corresponding responses were monitored during multiple (two) impacts. This technique was previously developed during testing of a steel stringer bridge for the purpose of damage detection. Although the application to the RTE 697 Bridge is the first time the technique has been applied to a concrete bridge, the field test procedure did not require modification.

Sample wave speed measurements are shown in Figures 18 and 19. Although original sampling was at 1,000 samples per second, the analysis technique employed to obtain wave speed estimates required a higher sampling interval for the accurate detection of (first) wave arrival. The result of a Fast Fourier Transform based interpolation scheme applied to the measured force pulse is shown in Figure 18, and a set of responses acquired across girder B is shown in Figure 19. The analysis procedure, made difficult because of the transition from ambient (or, preevent conditions) to actual first wave arrival, requires repeated estimates of wave arrival to assess variation in arrival times. As a result of the critical importance of identifying wave arrival times, this testing must be performed in the absence of elevated environmental noise (including traffic).

Results from the wave speed analysis provided estimates of wave propagation speeds between the location of impact and each end of each girder. Table 3 lists the wave speed estimates obtained during testing; the results are also plotted in Figure 19, along with error bars indicating standard deviation.

Table 3
Tabulated Wave Speed Results

Girder/Direction Ave	Wave Speed, ft/sec	Standard Deviation, ft/sec
AW	4174.79	85.566
AE	4173.913	0
BW	4965.7535	48.4314
BE	4369.414	224.7016
CW	4645.355	42.384
CE	4363.997	56.1061
DW	4470.588	332.756
DE	4120.885	75.0353



<u>Note:</u> Frequency response within each span has been normalized.

Figure 17. Measured (impact) response shapes for the first three bridge resonances

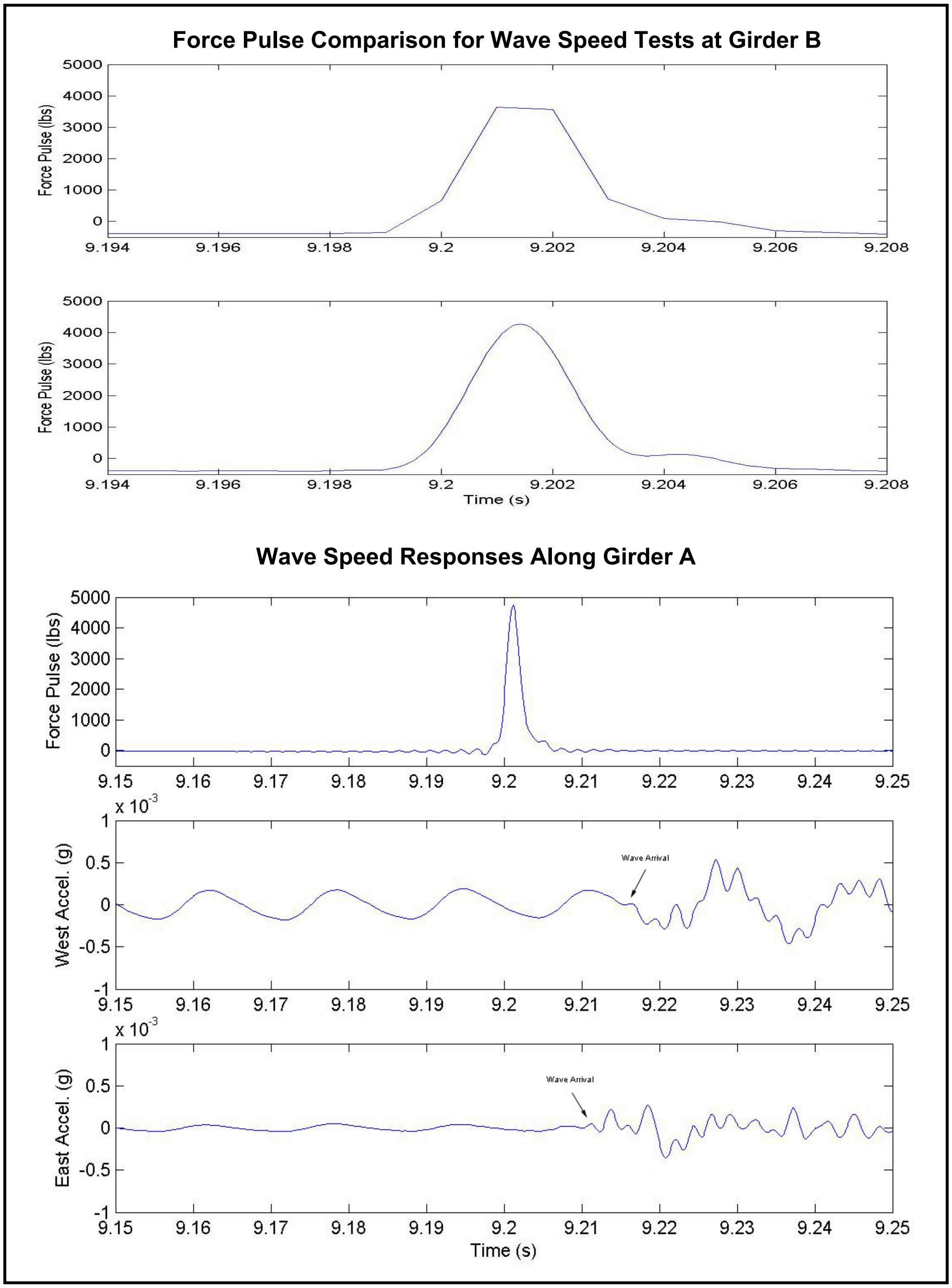
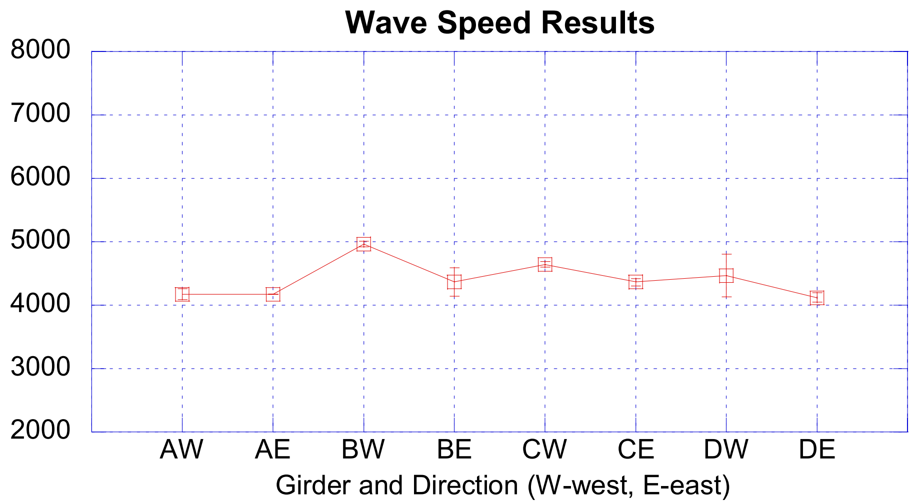


Figure 18. Wave speed responses measured along girders B and A



<u>Note:</u> Girder designation by letter and estimates are shown for propagation in both east and west directions. Error bars reflect the standard deviation for each estimate.

Figure 19. Comparison of estimated wave speeds

7 Discussion of Data Quality and Analysis Techniques

The data quality obtained during the ambient and impact tests at the RTE 697 Bridge are considered to be less than desirable based on the researchers' field experience. The inability to halt traffic flow over the bridge during ambient testing resulted in amplifier gain settings that were only 60 percent of what is typically employed. During the impact tests, the unavoidable presence of the gas generator and the resulting 60-Hz component superimposed on all transient response measurements nearly masked the bridge behavior and made it difficult to assess data quality during testing.

A series of time domain-based data-processing techniques were used to "clean" measured responses of artificially imposed characteristics that included nonzero mean offsets, low-frequency trends, and 60-Hz noise. Time domain (tapering) windows were imposed on the measured responses to reduce the presence of high-frequency content in the spectral estimates and to improve coherence. The low-frequency trend seen in the response, shown in Figure 6 (top), was not investigated as actual bridge behavior. While it is possible that this trend was the result of thermal drift in the bridge itself, further investigation is needed before this can be confidently labeled as such.

The field test techniques employed at the RTE 697 Bridge have been previously employed by research investigators on a variety of structures including bridges, dams, and buildings. In each case, however, care is often taken to ensure adequate energy is transmitted into all parts of the structure under test. In the case of the tests on the RTE 697 Bridge, however, it became apparent during testing and especially while reviewing the analysis results that significant amounts of energy were lost between spans—particularly during the impact tests. The particular construction of the deck in which three separate spans share interior support piers, however, allowed a normalization technique within each span to be pursued.

Normalizing the FRF response within each span allowed the relative characteristics within each span to be preserved, even at the expense of losing the relative magnitude information between spans. The identification of response shapes was facilitated by this normalization approach, although a close examination of the animated response in Figure 15 reveals motion in each span, which was detected during the impact tests. The identification of the response shapes obtained from the ambient results benefited from this approach. However, this information could have been slightly improved by a higher signal-to-noise ratio content.

8 Diagnostic Field Testing–Suggested Approaches

As a result of the tests conducted on the RTE 697 Bridge, diagnostic field-testing in which impact, ambient, and wave speed tests are combined provides some indication of how bridge condition may be proposed. The preferred diagnostic procedure appears to involve the use of impact testing along with wave speed testing to obtain resonant frequencies and response shapes and to assess whether girder condition varies across the bridge. Based on a review of the impact results and on the basis of the relatively small variations in wave speed between girders, the condition of RTE 697 Bridge would appear to be good. The use of ambient testing to assess bridge condition may not provide the excitation levels necessary to induce full system resonances and may not be sufficiently reliable in terms of repeated testing over the life of the bridge. However, the effectiveness of ambient testing may be improved by placing a fixed reference measurement in each span and employing the normalization technique to examine response shape geometry.

For a multiple-span bridge of this type, impact testing as conducted may provide satisfactory information for determining fundamental response characteristics, particularly in light of the normalized span approach to response shape determination. The attractiveness of the wave speed technique lies with the ability to propagate a pulse along a support girder across any pads or piers that may be present. The resulting wave speed estimate can be viewed as a characteristic for that girder that can be periodically monitored for reduced speeds over the life of the bridge. Furthermore, in assessing the condition of a bridge, wave speed estimates can aid the visual inspection of probable damaged sites in the bridge.

9 Summary and Conclusions

Field testing of a concrete bridge has been completed in which ambient, impact, and wave speed testing were performed. The purpose of these tests was to determine fundamental bridge response characteristics and to assess field procedures that might be suitable for assessment of bridge condition.

Ambient response measurements were observed to be of less than adequate quality because of the relatively large transients induced in the bridge by passing vehicular traffic during testing. Signal-processing techniques were successfully applied to the measured responses to provide spectral estimates with coherence levels that approached unity for candidate resonances in the bridge.

Transient response measurements obtained during impact testing suffered from the presence of a large-amplitude 60-Hz component that masked bridge response resulting from each impact. Although an analog band-pass filter (with cutoffs set at 30 mHz and 25 Hz) was applied to each acceleration response during acquisition, the filter roll-off was not steep enough to completely remove the 60-Hz signal. Digital filtering techniques were applied to the measured transient responses. These techniques were effective in removing the unwanted 60-Hz component.

Wave speed measurements acquired along each support girder were of sufficient quality that the transition from ambient to (first) wave arrival was clearly observed. An interpolation scheme was used to enhance the time interval resolution allowing more precise estimates of wave arrival times. For each girder tested, multiple estimates of arrival times and corresponding wave speeds were made.

Response shapes for each identified resonant frequency from both ambient and impact test results indicate expected bridge response behavior. The fundamental response is shown to be primary bending, while the second resonance is primary torsion. A third resonance below 25 Hz was identified and corresponded to a higher order bending behavior that revealed a saddle response in each span.

An overview of the various testing techniques applied to the RTE 697 Bridge appears to suggest that diagnostic procedures could be effective in identifying fundamental response characteristics. Normalizing responses within each span (for both ambient and impact results) provides clear indication of response shape geometry. Even in the presence of reduced amplitudes (particularly at locations removed from either the point of impact or from the fixed reference location), relative response behavior within each span is still preserved.

Ambient testing can provide insight into bridge behavior; however, it is recommended that testing be performed with fixed reference locations in each span. Impact testing provides adequate signal strength across the bridge, and resulting spectral estimates give clear indications of resonant frequencies. Wave speed estimates along each girder provide a simple, yet accurate indication of condition along each girder and can be incorporated in periodic field inspections.

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14. ABSTRACT

The U.S. Army Engineer Research and Development Center (ERDC) is leading research efforts for the development of rapid bridge load-capacity assessment tools for the military, otherwise known as Military Load Classification (MLC). These tools may be used in the evaluation of the effects of heavy military-vehicles on civilian bridges and are based, in part, on field tests of concrete bridges. This field testing procedure is aimed at determining the MLC of a bridge by first estimating girder stiffness and considering load distribution effects associated with a test vehicle. This approach, while capable of providing the desired MLC estimate, does not provide an adequate measure of uncertainty or confidence in the estimate, since the field measurement may mask actual damage states in the bridge.

Assessing the current condition of a bridge is a key component in the determination of its load-carrying capacity. As a result, tests in which the true condition of the bridge is determined can be useful in assessing the relative uncertainty or even the appropriate confidence level of the MLC estimate. This study describes field testing procedures using ambient, impact, and wave speed techniques on reinforced concrete bridges owned by the Virginia Department of Transportation. The ambient response measurements were used to determine fundamental characteristics including resonant frequencies and mode shapes, while the transient tests were designed to provide some measure of the relative condition that may exist between girders in the bridge. These measurements will supplement other measurements acquired using test vehicles and surveying techniques.

15. SUBJECT TERMS

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